Suppression of the bottleneck in semiconductor microcavities

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Abstract

The relaxation kinetics of cavity polaritons by scattering with thermal acoustic phonons is studied within the rate equation approximation. Numerical results show that a suppression of the bottleneck of lower polariton states occurs at high polariton densities. We have found that the long decay time of the photon-like polaritons, the thin width of the embedded quantum wells and the small value of exciton-cavity detuning are favorable for the suppression of the bottleneck.

1 Introduction

Semiconductor microcavities (MC) with embedded quantum wells have found a growing interest in recent years. The eigenstates of the systems as a result of the strong coupling between the MC photon and quantum well exciton at the same in-plane wave vector are called cavity polaritons. The Rabi splitting and the dispersion of these cavity polaritons are readily observable using reflection, absorption, photoluminescence measurements [1-3]. Recently, many new phenomena have been intensely studied in MC: super-linear behaviour in emission intensity [4-6], stimulated polariton amplifier [7-8] and suppression of the relaxation bottleneck [9]. To the best of our knowledge, Tartakovski et al. [9] were the only group, which has clearly observed this suppression of the relaxation bottleneck of lower polariton states at higher powers.

In this work, we study the relaxation kinetics of cavity polaritons by scattering with thermal acoustic phonons. Here we will present numerical solutions of the rate equations and show that a suppression of the bottleneck occurs at sufficiently high concentration of the polaritons.

2 Relaxation kinetics of cavity polaritons

Within the two-coupled band model and considering only the 1s state of the heavy-hole quantum well exciton, the energy for the upper and lower cavity polariton branches is given by the usual solutions of the polariton dispersion equations as given in Ref. [10]:

$$(E_k^x - E_k^i)(E_k^c - E_k^i) = \frac{\hbar^2 \Omega^2}{4} \tag{1}$$

where

$$E_k^c = \sqrt{(E_0^c)^2 + \frac{\hbar^2 c^2}{\epsilon_{cav}} k^2} \tag{2}$$

$$E_k^x = E_0^x + \frac{\hbar^2 k^2}{2(m_e + m_h)} \tag{3}$$

Here E_0^x is the fundamental exciton energy, m_e (m_h) the electron (hole) in-plane mass, n_{cav} the cavity refraction index, Ω the Rabi splitting. Fig. 1 shows the cavity polariton dispersion of GaAs quantum wells embedded in cavity for a detuning $\delta = E_0^c - E_0^x = -2$ meV, a Rabi splitting $\hbar\Omega = 4.8$ meV, and $n_{cav} = \sqrt{\epsilon_{cav}} = 3.07$.

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In the following we will use the semi-classical Boltzmann kinetics to investigate the cavity polariton relaxation by acoustic phonon scattering. The rate equation for the distribution f_k^i of branch i with the in-plane wave vector k and energy E_k^i of the cavity polariton can be written as [10-11]

$$\frac{\partial}{\partial t} f_k^i = -\frac{f_k^i}{\tau_k^i} - \sum_{j, \overrightarrow{k}} \left[W_{\overrightarrow{k}, \overrightarrow{k}'}^{i,j} f_k^i \left(1 + f_{k'}^j \right) - \left(\overrightarrow{k}, i \rightleftharpoons \overrightarrow{k}', j \right) \right] + G_k^i(t) \tag{4}$$

$\frac{1}{\tau_k^i}$ is the radiative recombination rate and $G_k^i(t) \equiv A_k^i H(t)$ the generation rate. The transition rates $W_{\overrightarrow{k}, \overrightarrow{k}'}^{i,j}$ due to deformation potential scattering are weighted with exciton Hopfield coefficients x_k^i and $x_{k'}^j$:

$$\begin{aligned} W_{\overrightarrow{k}, \overrightarrow{k}'}^{i,j} = {} & \frac{L_z \left(x_k^i x_{k'}^j \right)^2}{\hbar \rho V u^2 q_z} \left(\Delta_{k,k'}^{i,j} \right)^2 A^2(q_z) D^2(|\overrightarrow{k} - \overrightarrow{k}'|) \\ & \left| N_{E_{k'}^j - E_k^i}^p \right| \Theta \left(\Delta_{k,k'}^{i,j} - |\overrightarrow{k} - \overrightarrow{k}'| \right) \end{aligned} \tag{5}$$

where

$$\Delta_{k,k'}^{i,j} = \frac{\left| E_k^i - E_{k'}^j \right|}{\hbar u} \tag{6}$$

$$q_z = \sqrt{\left(\Delta_{k.k'}^{i,j} \right)^2 - |\overrightarrow{k} - \overrightarrow{k}'|^2} \tag{7}$$

$$D(x) = D_e G \left(\frac{x m_h}{m_e + m_h} \right) - D_h G \left(\frac{x m_e}{m_e + m_h} \right) \tag{8}$$

$$A(x) = \frac{8\pi^2}{L_z x \left(4\pi^2 - L_z^2 x^2 \right)} \sin \left(\frac{L_z x}{2} \right) \tag{9}$$

$$G(x) = \frac{1}{\left[1 + (x a_b/2)^2 \right]^{3/2}} . \tag{10}$$

Here L_z is quantum well width, V the sample volume, u the longitudinal sound velocity , ρ the mass density of the solid, D_e and D_h the deformation potentials. A(x) and G(x) are the Fourier transform of $\chi_e^2(z_e)$ and $F^2(\rho)$, respectively. Note that the 1s exciton wave function has been taken in the simplest form

$$\phi_x^{1s}(r_e, r_h) = F(\rho) \chi_e(z_e) \chi_h(z_h) \frac{1}{\sqrt{S}} e^{i \overrightarrow{k} \overrightarrow{R}}. \tag{11}$$

Expression (5) contains transition rate due to the absorption of phonon $\propto N_E^p$ for $E > 0$, and due to emission of phonon $\propto \left(N_{|E|}^p + 1 \right)$ for $E < 0$, where $N_{E>0}^p = \left(e^{\beta E} - 1 \right)^{-1}$ is the thermal phonon distribution function.

In the following we will present the results of the cavity polariton kinetics on the lower branch assuming an isotropic distribution of polaritons in k space. For the decay rate $\frac{1}{\tau_k^i}$, we use the same approximation given by Bloch and Marzin in GaAs quantum well [11]: $\frac{1}{\tau_k^i} = \frac{\left(c_k^i \right)^2}{\tau^c}$ for $0 < k < k_{cav} = 6 \times 10^4 \ cm^{-1}$; $\frac{1}{\tau_k^i} = \frac{1}{\tau^x}$ for $k_{cav} < k < k_{rad} = \frac{n_{cav} E_0^x}{\hbar c} = 2.1 \times 10^5 \ cm^{-1}$; and $\frac{1}{\tau_k^i} = 0$ for $k > k_{rad}$, (τ^c and τ^x are the radiative life of photon and exciton, respectively, c_k^i the photon Hopfield coefficient).

3 Numerical results for kinetics of cavity polaritons

In this section, rate equations are numerically integrated using the following parameters for MC with embedded GaAs quantum wells: [12-13] $E_0^x = 1.3955 \ eV$, $m_e = 0.067 m_0$, $m_h = 0.13 m_0$, $\hbar \Omega = 4.8 \ meV$, $a_b = 7.5 \ nm$, $D_h = 12 \ eV$, $D_e = -7 \ eV$ [14], $u = 4.81 \times 10^3 \ m/s$, $\rho = 5.3 \times 10^3 \ kg/m^3$, $n_{cav} =$

3.07, $\tau_x = 200\ ps$. Concerning the generation rate we choose for A_k^i a Gausian distribution of exciton on the lower branch with a width $\Delta E = 0.1\ meV$ centered at a momentum $k_0 = 5 \times 10^5\ cm^{-1}$ and $H(t) = H_0\ th\left(\frac{t}{T}\right)$ with $T = 20\ ps$. Unless otherwise stated we will choose $L_z = 6\ nm$, $T_{phon} = 2\ K$, $\delta = E_0^c - E_0^x = -1\ meV$.

In Fig. 2 we show the distribution function $f_k(t)$ of cavity polaritons on the lower branch for a rather long radiative photon decay time $\tau_c = 50\ ps$ at $n = 7.8 \times 10^9\ cm^{-2}$. We clearly see the presence of the bottleneck effect similar to the bulk case [15-16]. However, if we increase the pump intensity, a suppression of the bottleneck occurs as can be clearly seen in Fig. 3 at $n = 5.1 \times 10^{10}\ cm^{-2}$. These findings agree rather well with recent measurements performed in GaAs cavity by Tartakovski et al. [9] using nonresonant cw laser excitation. They found that the bottleneck has been strongly suppressed at higher power laser excitation. This feature is specific for cavity polaritons. We have also carried out the calculations for the ortho-exciton polaritons in bulk Cu_2O [16] and have found that the bottleneck persists up to very high density around $10^{18}\ cm^{-3}$. The main difference in the dispersion relation between cavity polaritons and bulk polaritons is the slope of E_k versus k in the bottleneck k-region. The very high value of the slope of the bulk polaritons (70 times higher than the slope of the cavity polaritons) is very unfavorable for the suppression of the bottleneck even at very high densities. On the other hand, one can lower the slope in the cavity polaritons by decreasing the absolute value of the negative detuning δ. From expression (9) of $A(x)$ we can see that the scattering rate is roughly proportional to $\left(sin\frac{L_z}{2}/L_z\right)^2$. Therefore, quantum wells with thin width will be favorable for the suppression of the bottleneck. For $L_z = 3\ nm$, $\delta = -0.25\ meV$ and $\tau_c = 50\ ps$ the bottleneck starts to be suppressed at densities, which are roughly 3 time lower than those for $L_z = 6\ nm$, $\delta = -1\ meV$ and $\tau_c = 50\ ps$. For a more realistic τ_c one needs a higher density to compensate the fast decay of the photon-like polaritons. Recently, Senellart and Bloch have given the photon decay time τ_c a value of 6.6 ps [17]. In Fig. 4 we display the integrated distribution function $\left(\int_0^\infty dt f_k(t)\right)$ versus the wave number k for different polariton densities for $\tau_c = 6.6\ ps$, $L_z = 3\ nm$, $\delta = -0.25\ meV$ at 2K (Fig. 4a) and 15K (Fig. 4b). These results show a clear process of the relaxation kinetics: a nonlinear increase of low k cavity polaritons with increasing polariton densities (or excitation laser powers) leads to the suppression of the bottleneck. The suppression is slightly more favorable at T=15 K. For density $n > 10^{10}\ cm^{-2}$, one should take into account the exciton-exciton scattering and also go beyond the rate equation approximation. However, we expect our results remain qualitatively valid even in a better treatment of polariton relaxation kinetics.

In conclusion, we have presented detailed cavity polariton relaxation kinetics of lower branch due to deformation potential scattering by accoustic phonons. In agreement with recent experimental results by Tartakovski et al. [9] we found that suppression of the bottleneck is found at high polariton densities.

Acknowledgements

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Figure captions:

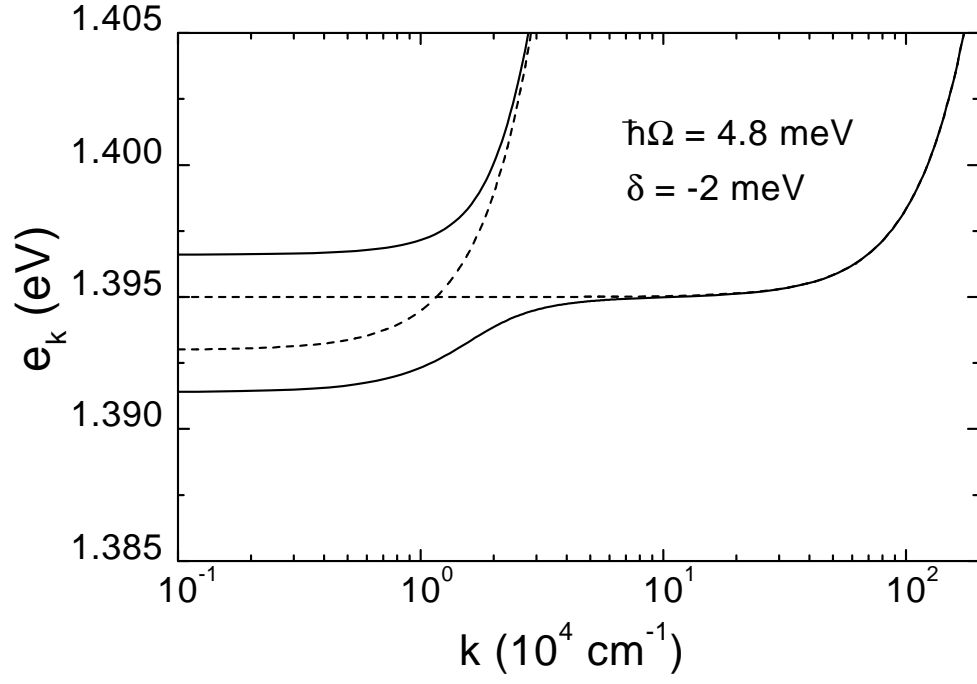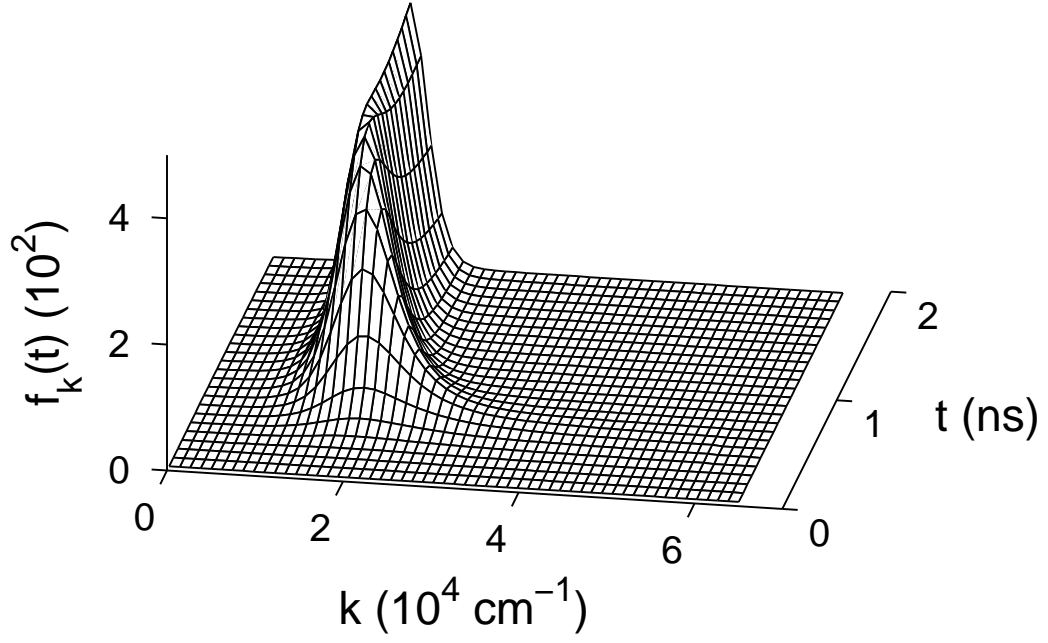**Fig. 1:** Dispersion of cavity polaritons with embedded GaAs quantum wells for $\delta = -2\ meV$, $\hbar\Omega = 4.8\ meV$.

Fig. 2: Resulting distributions of cavity polaritons on lower branch versus time for $\delta = -1\ meV$, $L_z = 6\ nm$, $\tau_c = 50\ ps$, $n = 7.8 \times 10^9\ cm^{-2}$ at a bath temperature of 2 K.

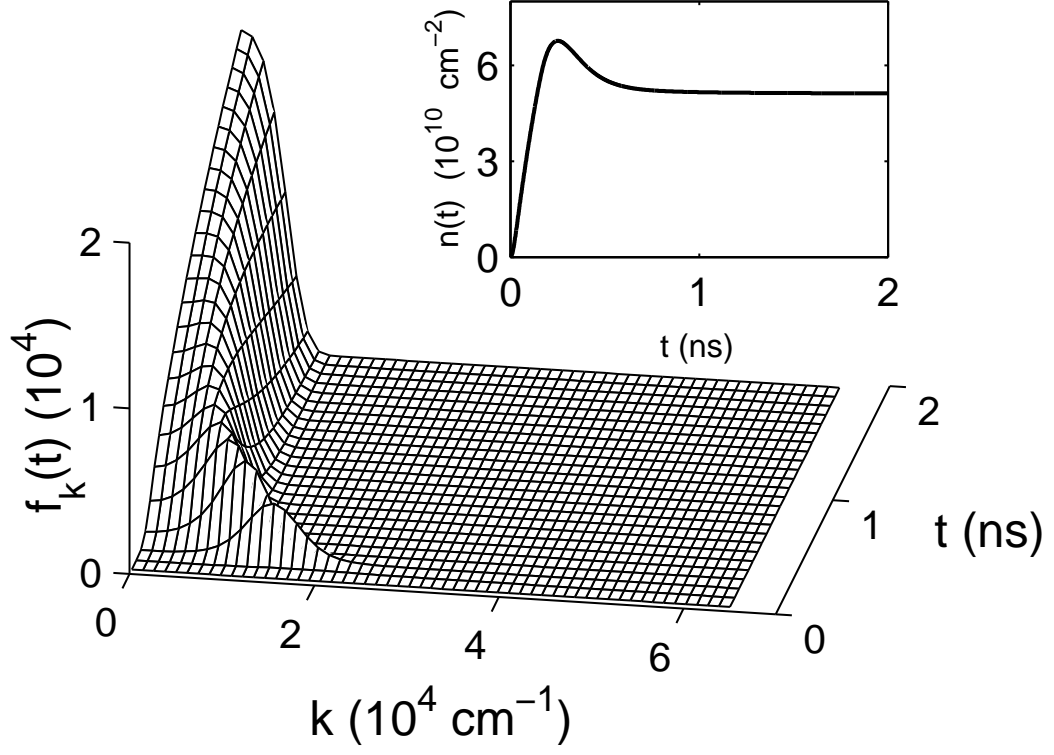**Fig. 3:** Suppression of the bottleneck at $n = 5.1 \times 10^{10}\ cm^{-2}$ for $\delta = -1\ meV$, $L_z = 6\ nm$, $\tau_c = 50\ ps$ and $T = 2\ K$. The inset shows total polariton density.

Fig. 4: Resulting integrated distribution function versus wave number k for different polariton densities at 2K (a) and 15K (b) for $\delta = -0.25\ meV$, $L_z = 3\ nm$, $\tau_c = 6.6\ ps$.

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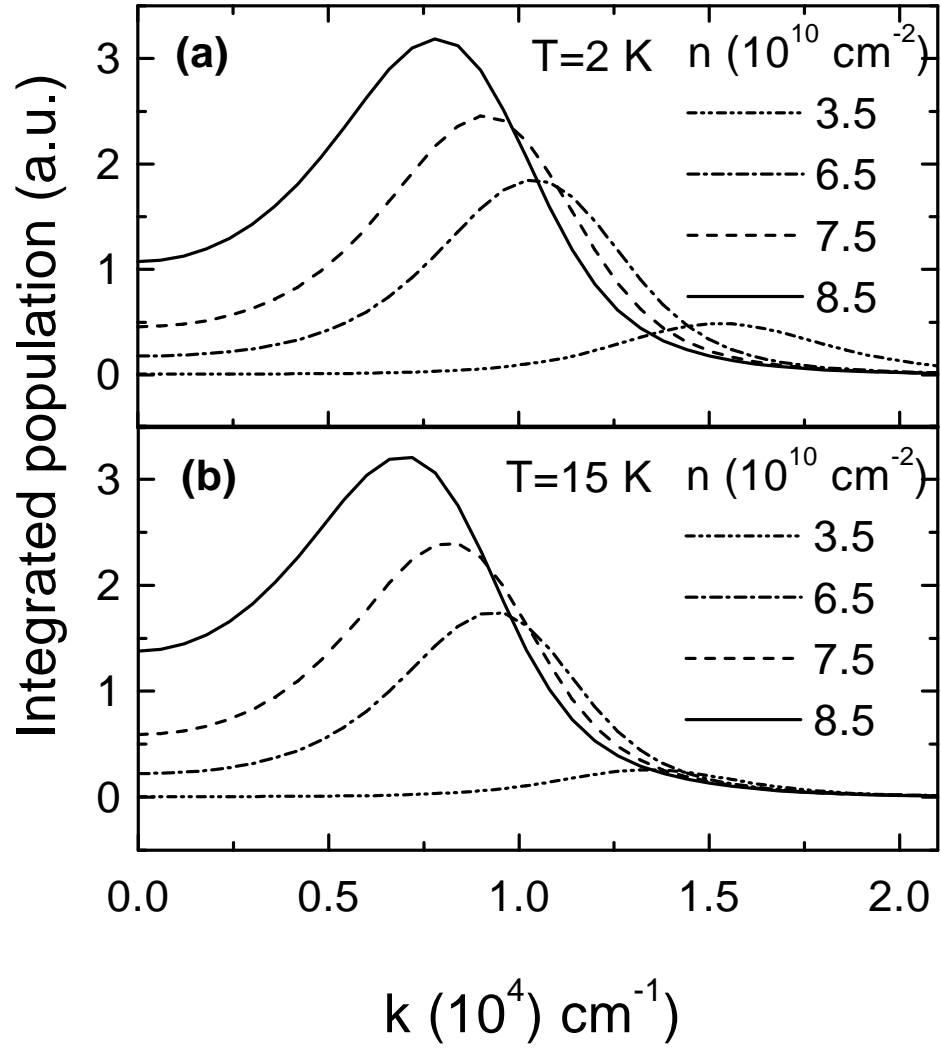
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Resulting integrated distribution function versus wave number k for different polariton densities at 2K (a) and 15K (b) for $\delta = -0.25\ meV$, $L_z = 3\ nm$, $\tau_c = 6.6\ ps$.